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WFIRST Coronagraph (CGI): Observing Scenario 6, rationale and modeling

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Overview

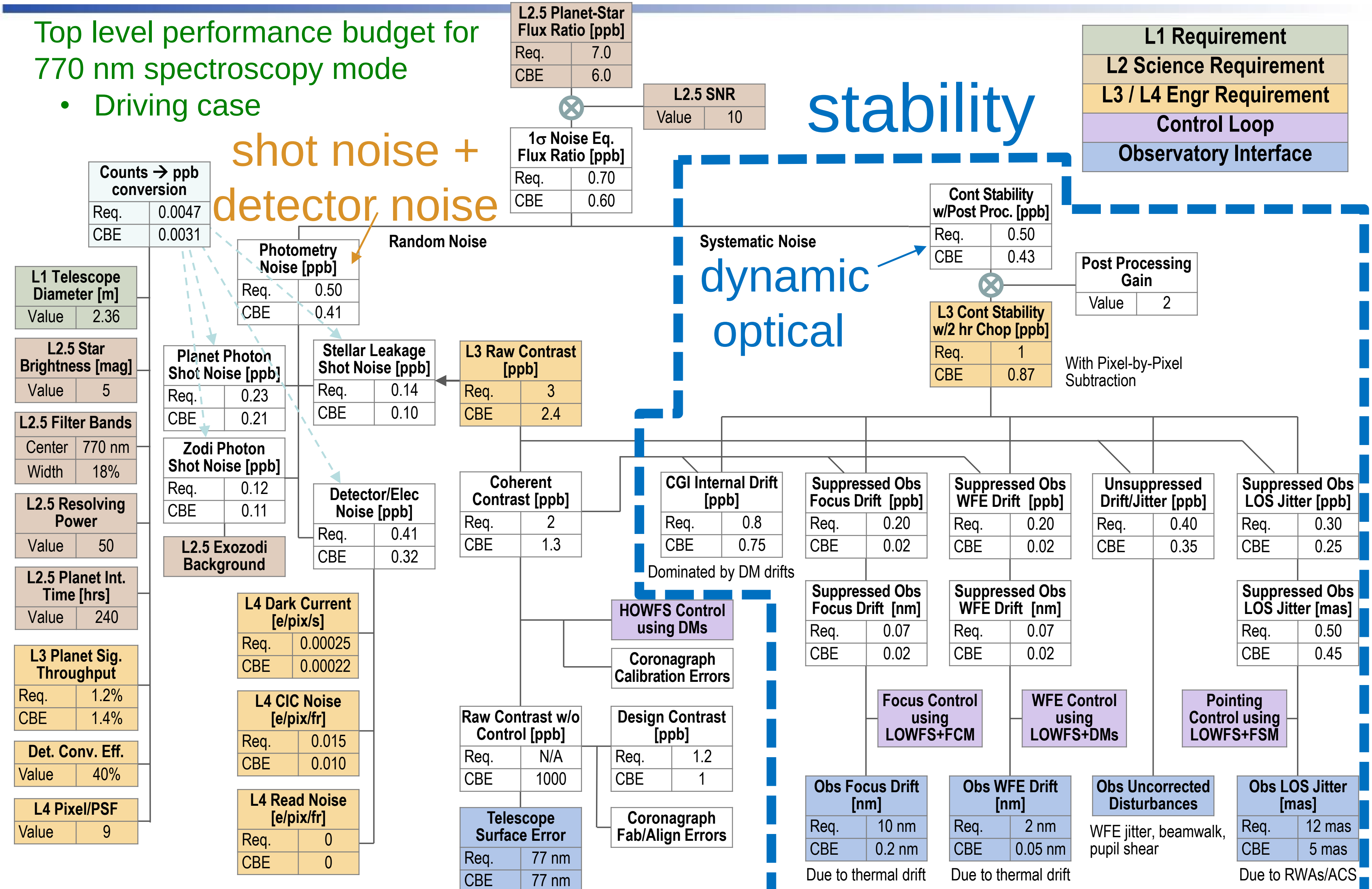
- Error budget context for stability metrics
- Operations effect on stability requirements
- Target catalog + bright star catalog
- STOP modeling results

Requirements / Error Budget Foundation

- **If raw contrast (residual starlight) were much lower than planet flux ratio, no special treatment would be necessary**
  - L2 requirement CGI-2.2 ~ 8e-9 flux ratio planet at 4 λ/D, SNR=10
  - L3 requirement CGI-L3.14 raw contrast 3e-9 at 3-4 λ/D
  - Can't get SNR=10 without subtracting raw contrast
- **Residuals from subtracting raw contrast include optical dynamic terms and measurement noise**
- **Optical dynamic terms:**
  - DM motion (uncommanded); DM settling times
  - Thermally induced WFE, considering LOWFS control
  - Changes in RWA jitter amplitudes (LoS and WFE)

Stability Error Budget from WIETR 8/16/17

Top level performance budget for 770 nm spectroscopy mode
- Driving case



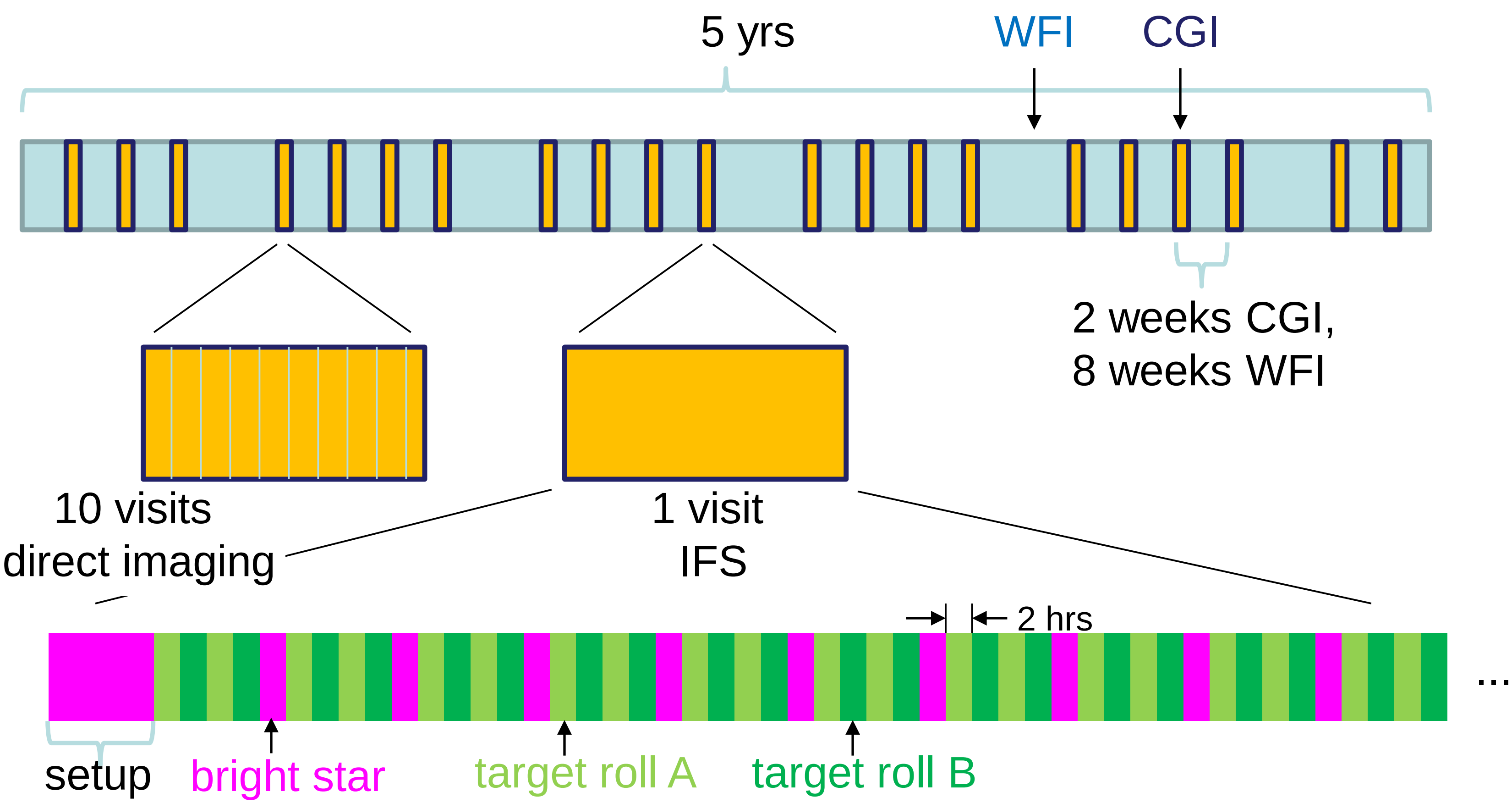
I. Poberezhskiy

Current context of “post-processing”

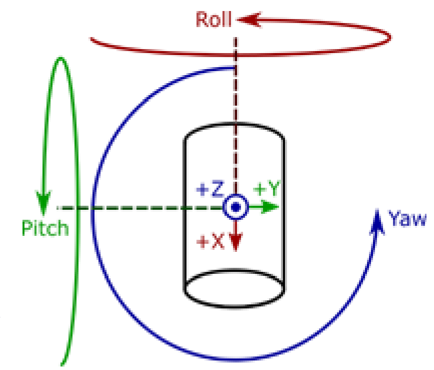
- **In early formulation of SNR calculations (circa 2014), f_{pp} post-processing factor related raw contrast to residuals after post-processing**
  - Notional f_{pp} = 1/10 or 1/30
  - Placeholder to carry forward until modeling quantification
- **Current baseline operation is differential imaging during a single visit, followed by post-processing incorporating mission-wide library**
  - “Contrast Stability” quantifies residuals from simple pixel-by-pixel differential image taken from single visit
  - Post-processing may use mission-wide image library, auxiliary data, spatial mode filtering
    - Notional f_{pp} = 1/2 on top of “Contrast Stability”

DRM gross cartoon

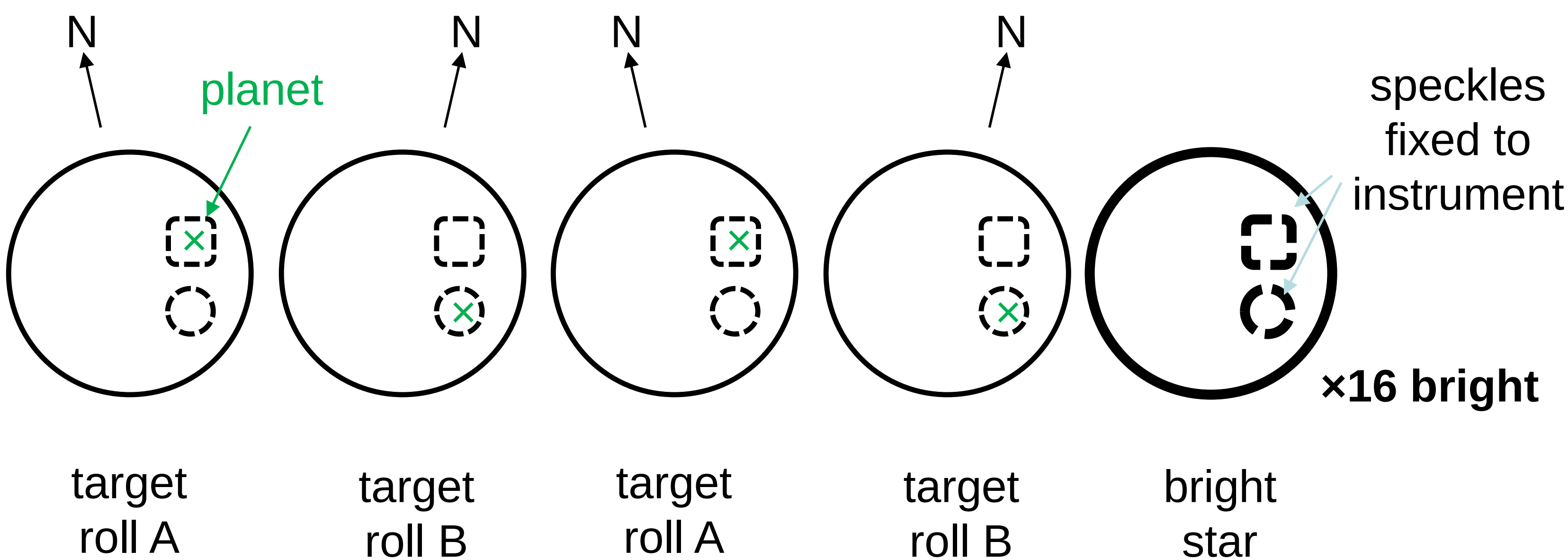
- **Observations are grouped by observing mode**
  - Mode is combination of coronagraph masks, band, orientation, IFS vs. DI, polarization optics
- **1/6 of 5-year mission is 41 weeks (after commissioning)**



Differential imaging options



- **Angular Differential Imaging (ADI) uses different roll angles on target star**
  - Operating constraints set roll $|\theta_x| < 15$ deg
    - Zero-point of roll references solar array to sun position
- **Reference Differential Imaging (RDI) uses another star**



ADI and RDI noise considerations

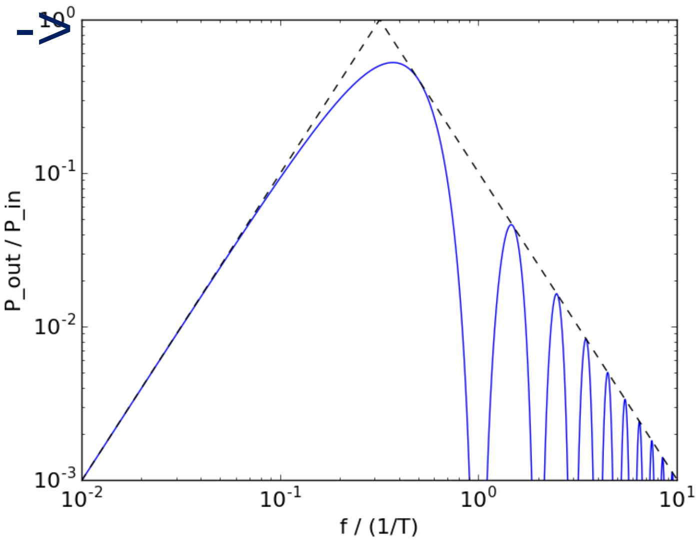
- **Time spent doing RDI includes time off-target**
  - RDI gets fewer planet photons
- **Performing ADI contains measurement noise from two photometric apertures, equally exposed**
  - ADI residuals contain $\sqrt{2}$ factor in measurement noise (detector noise, stellar shot noise) w.r.t. single photometric aperture
  - If RDI measurements can be made with lower measurement noise, residuals can approach that of single photometric aperture alone
- **In both cases, slew & settle overhead must be considered**
  - Overhead generally higher for RDI, compared to ADI using 26 deg

ADI and RDI fundamental considerations

- **ADI involves self-subtraction of exo-zodi / disk signatures**
  - For 26 deg roll, features with modest azimuthal structure are mostly absent in differential image
- **RDI may allow diversity of bright star choices**
  - Average out astrophysical confusion
- **RDI allows for construction of mission-wide library**
  - Unquantified benefit to post-processing
- **CGI Integrated Modeling tentatively shows that RDI with different spectral types (effective temperatures) introduces little error due to spectrum**
  - Allows use of early-type reference stars differenced against late-type target stars

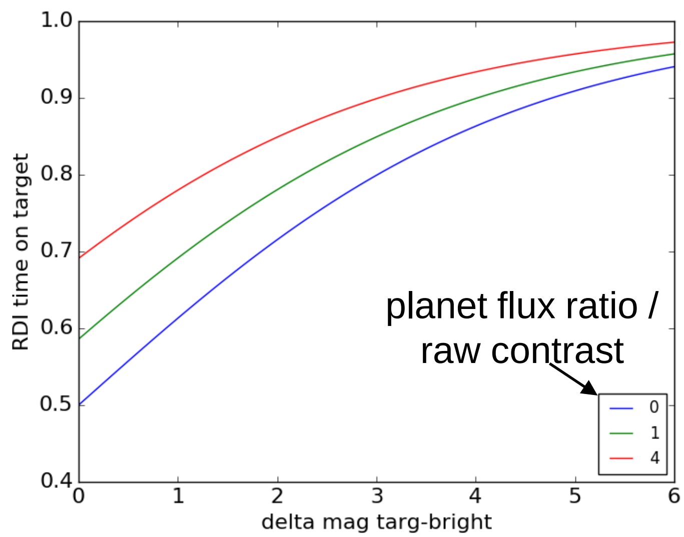
"Chop" mentality

- **Perform differencing on timescales short compared to dominant temporal frequencies of disturbances**
  - DM settling timescales > 100 hrs
  - Thermal timescales > 10 hrs
  - RWA timescales ~ hrs
- **Temporal filtering effect of differential**
  - Integrate for time *T* -> temporal convolution by top-hat
  - Difference successive *T* periods -> convolution with +/- delta fn
  - In frequency space, filter amplitudes by $\sin(\pi f T)^2/(\pi f T)$
  - Asymptotes to $(\pi f T)^2$ power for small *f*, $1/(\pi f T)^2$ power for large *f*



Factors in OS6 construction (1)

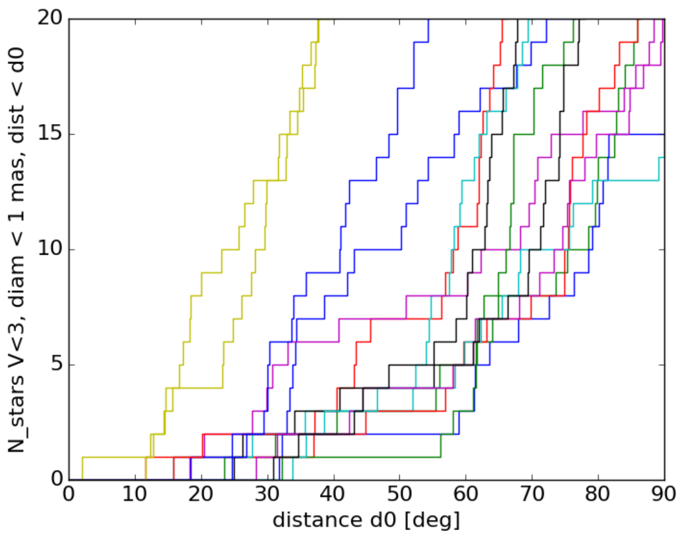
- **OS6 balances slew/settle overhead, available bright stars, and desire for short chop period**
  - Brighter stars require less time off-target
    - If dominated by Poisson noise, when bright star ~ 3 mag brighter than target, spend ~ 20% of time on bright star
    - If detector noise dominated, spend much less time on bright star



Factors in OS6 construction (2)

- **Availability of bright stars is factor**
  - Require *V* < 3, stellar angular diameter < 1 mas
    - Implicitly, these must be hot stars (A2 and hotter)
  - Not yet screened for multiplicity (~ 50%)
- **Check each of 15 RV target stars for distances to *V* < 3, diameter < 1 mas stars**
  - Most targets have a bright star < 30 deg away
- **RDI to bright star *V* < 3 has similar slew/settle overhead w.r.t. 26 deg roll**

each of 15 RV target stars

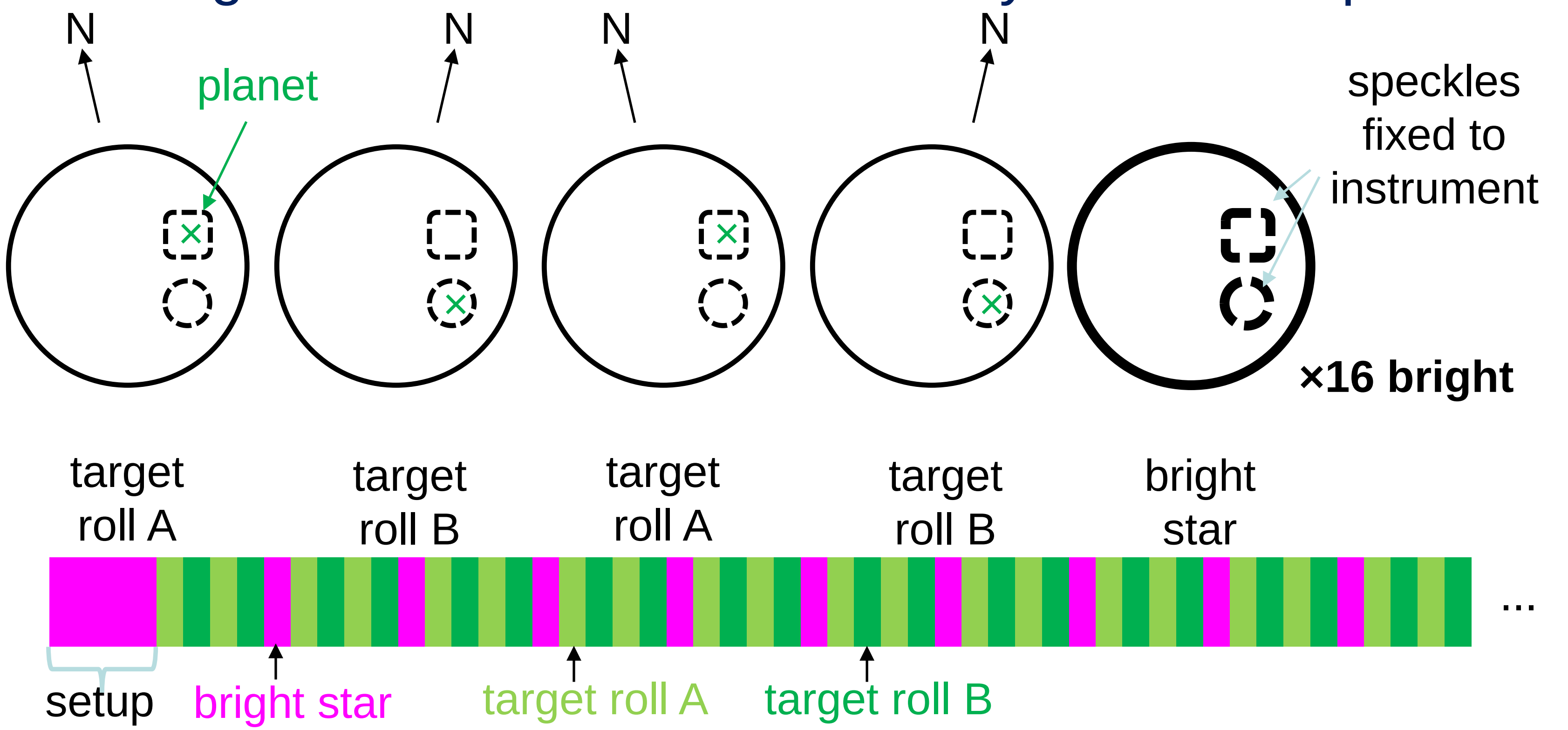


Factors in OS6 construction (3)

- **Slew/settle time is ~ 11 minutes for 26 deg roll or slew**
  - Approximately 3 deg/min plus 2.5 min fixed time
- **Want to enable RDI with 80% / 20% target / bright star duty cycle**
  - Appropriate for $\Delta V = 3$ Poisson noise considerations on a low-flux planet
- **Choose nominal ~ 10% overhead from slew/settle**
  - 12 minutes for 30 deg slew is 10% of a 120 min interval
- **Given 2 hr bright-star observation, want 8 hrs on target**
- **Little harm in ADI-like observation while on-target**
  - Again choose 2 hr chop based on 10% overhead, 11 min

OS6 as RDI + ADI

- **For arbitrary observation, break into 10 hr cycles**
  - Each cycle has A-B-A-B-bright 2 hr intervals
- **Beginning of visit has 8 hr EFC setup**
  - 8 hr is not yet well justified
  - Long observations almost certainly will want repeat EFC



STOP model inputs

- **Need specific case for modeling inputs**
  - Keep 47 UMa as target for consistency with OS3, OS5
  - Time of year determines sun position
    - Sun determines observing constraints, thermal impact of slew
  - Choose η UMa as nearby bright star
    - Previous choice was β UMa, but β UMa is > 1 mas
    - η UMa is good choice for 47 UMa during particular times of the year
  - Choose median thermal impact
    - Can manipulate schedule to get better or worse days
- **Calculate for 13 cycles of 10 hrs each**
  - 94 hrs on target

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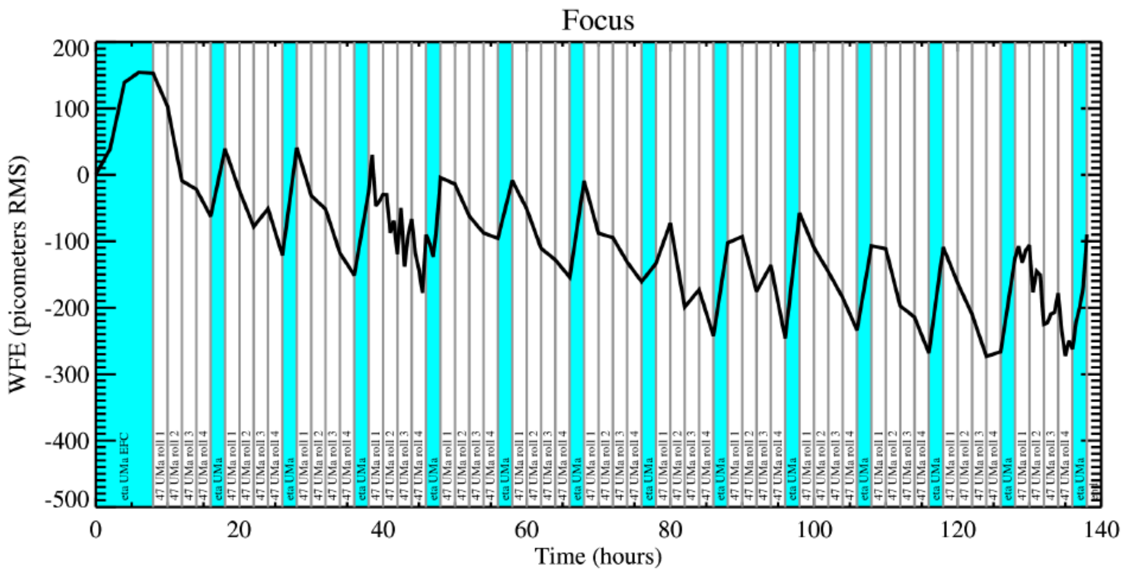
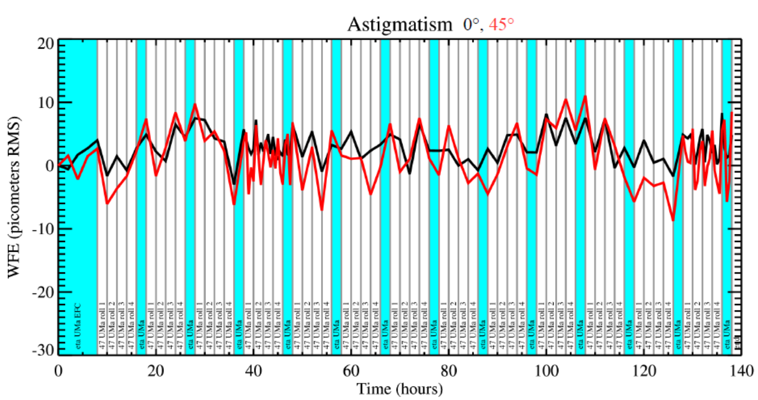
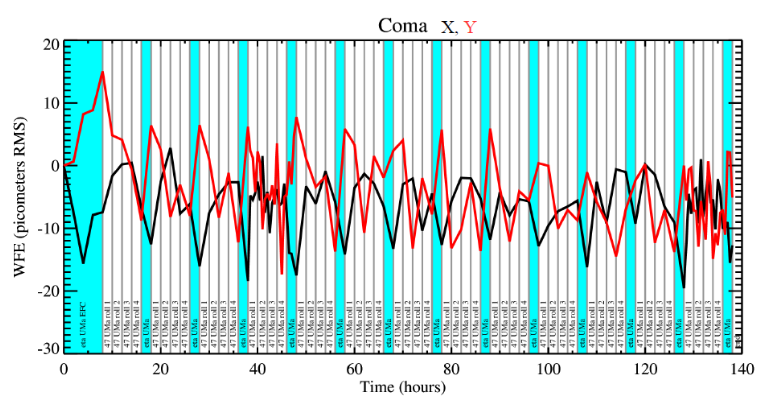
STOP model results





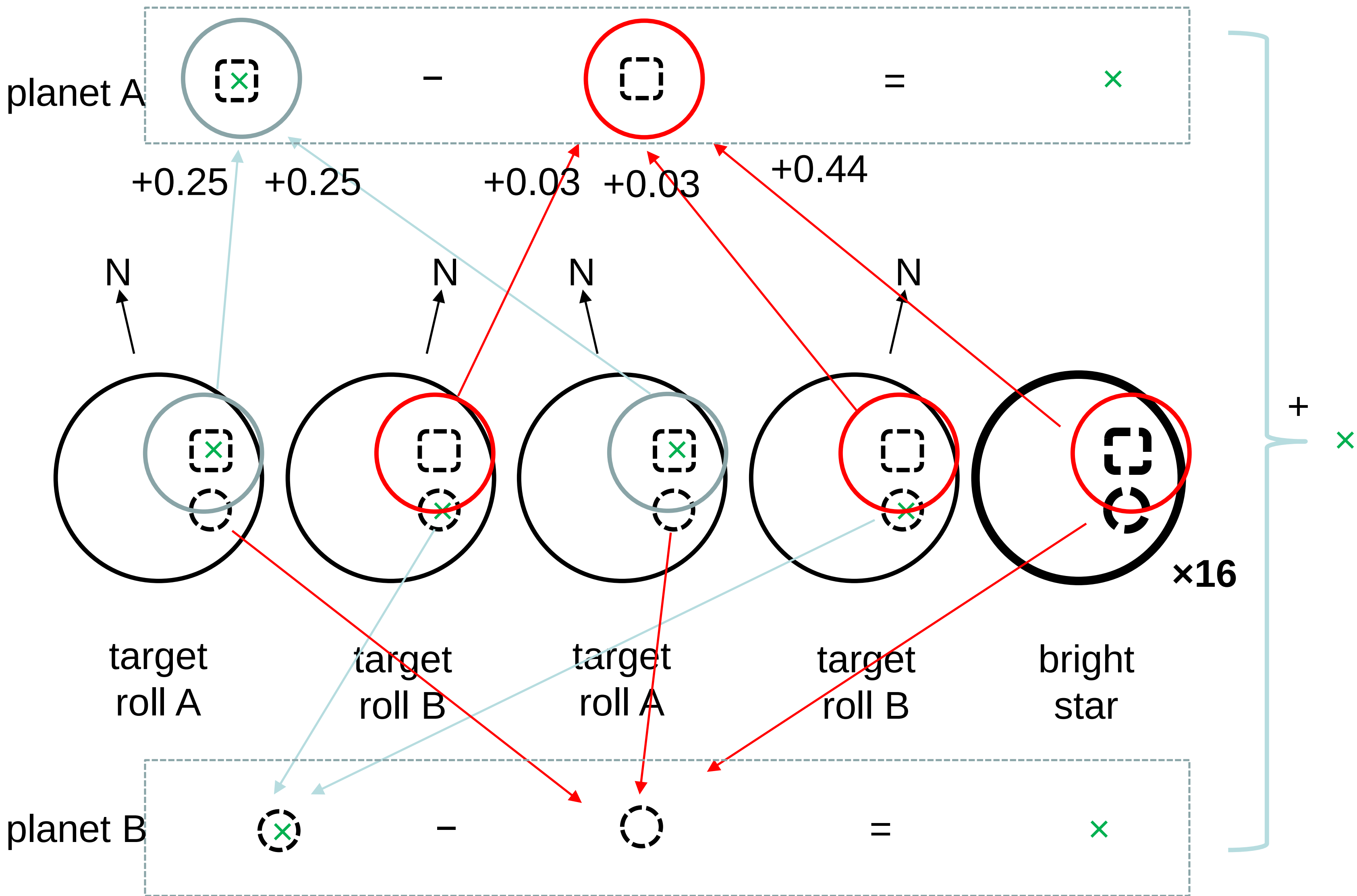


Missing pieces

- **Non-thermal materials dynamics**
  - Outgassing, drying, creep, growth
- **Update target list, use Gaia catalog instead of Yale**
  - Not much evolution of understanding of $V < 3$ stars
- **Multiplicity of entries in bright star catalog**
- **Quantify errors introduced by differencing speckle fields of different effective temperatures**

BACKUP SLIDES

ADI + RDI calculations



10 aperture measurements per cycle for one residual planet aperture

define photometric weights

- **Arrange intensity measurements into columns (pointing) and rows (two locations)**

$I_{bkg} + I_{pl}$	I_{bkg}	$I_{bkg} + I_{pl}$	I_{bkg}	I_{bkg}
I_{bkg}	$I_{bkg} + I_{pl}$	I_{bkg}	$I_{bkg} + I_{pl}$	I_{bkg}

- **Parametrize negative (non-planet) weights by $0 \le w_{ref} \le 1$**
  - This is scale of ADI ($w_{ref} = 0$) to RDI ($w_{ref} = 1$)

0.25	$-(1-w_{ref})/4$	0.25	$-(1-w_{ref})/4$	$-w_{ref}/2$
$-(1-w_{ref})/4$	0.25	$-(1-w_{ref})/4$	0.25	$-w_{ref}/2$

No single "best" weighting approach

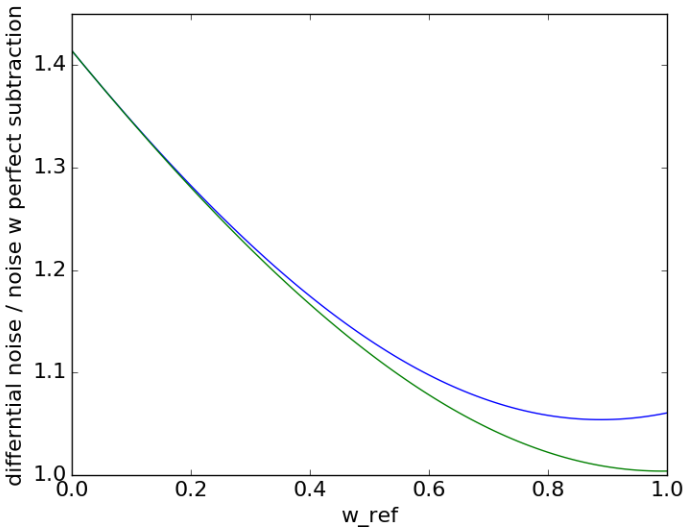
- Effectiveness of chopping in subtracting slow variations is diluted when $w_{ref} > 0$
- Weighting that is best for Poisson noise is not best for temporal chopping (RDI + ADI)
- Weighting that is best for detector noise ($w_{ref} \sim 1$) is not best for temporal chopping
- Weighting that is best for chopping is ADI alone ($w_{ref} = 0$)

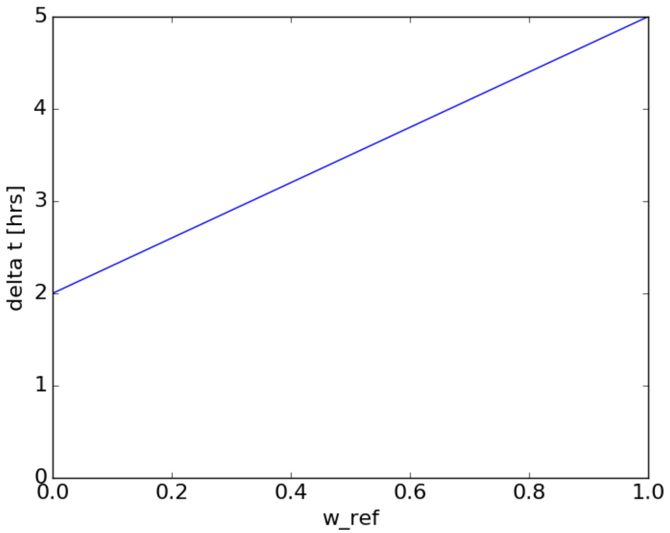
ADI	0.25	-0.25	0.25	-0.25	
	-0.25	0.25	-0.25	0.25	

RDI	0.25		0.25		-0.5
		0.25		0.25	-0.5

Dependence on w_{ref}

- For calculation, assume ratio of bright star to target star is B=16 (ΔV=3), all pointing overheads equal to each other
- Previous calcs include no measurement noise (shot + detector)





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What OS6 w_{ref} should we choose

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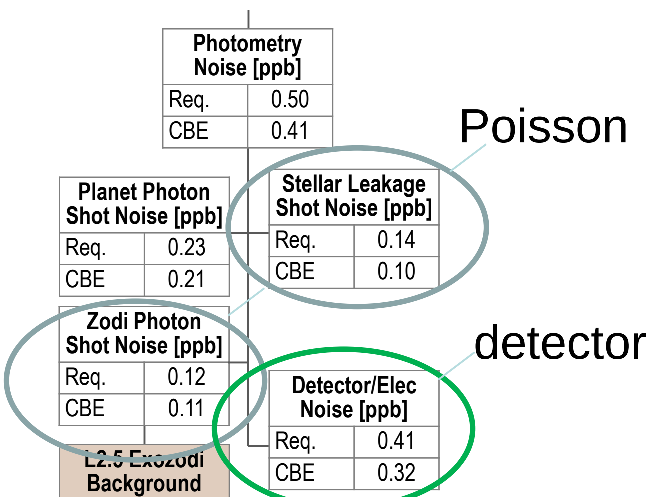
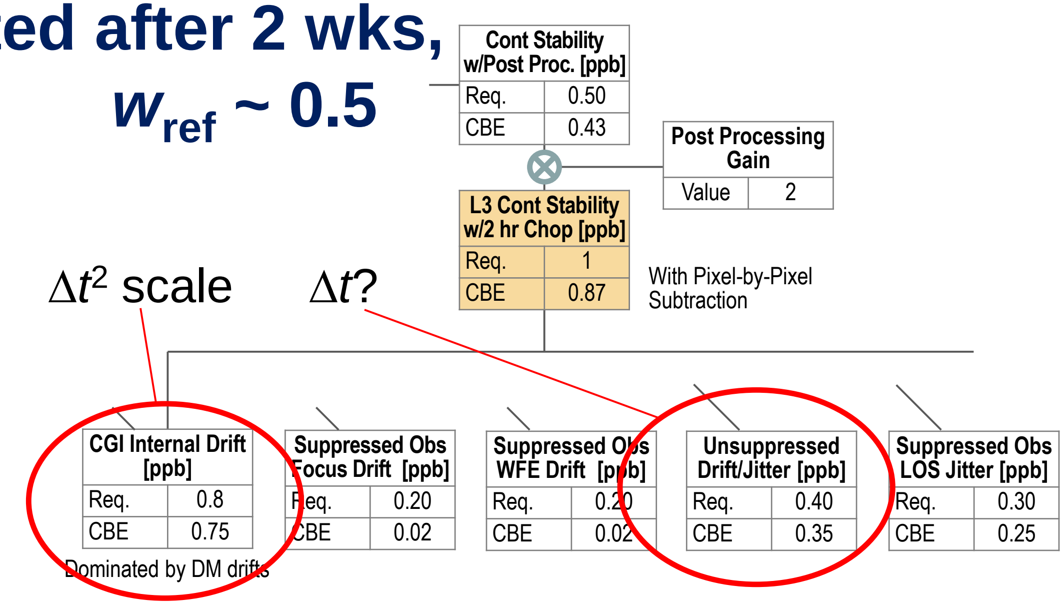
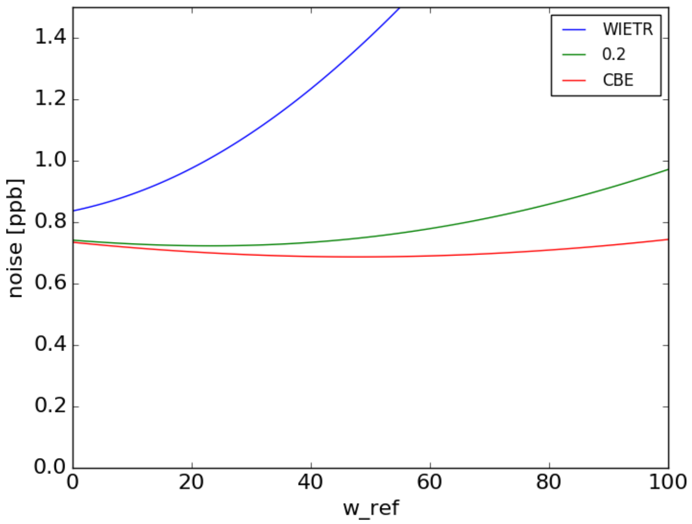
- **Remember that w_{ref} is an analysis parameter, data can be analyzed as a function of w_{ref} (all values 0-1)**
- **Take exact Req. numbers from WIETR, w_{ref}=0 (ADI)**
- **Change DM number to 0.2 in 2 hrs, w_{ref} ~ 1/3**
  - DM 0.2 in 2 hrs only requires 16 hrs since mode change, 0.45 for w_{ref}
- **Change DM to expected after 2 wks, w_{ref} ~ 0.5**





OS6 w_{ref}

- **Choice of OS6 + w_{ref} depend strongly on assumptions about dynamic behavior**
  - Need more detailed analysis; not just linear / quadratic eyeball guess
- **Detector noise terms are far less uncertain**
  - Extra noise at small w_{ref} is correct
- **Likely want to baseline $0.5 < w_{ref} < 0.75$**
  - This is 3.5 hrs < Δt < 4.25 hrs
- **Assume Δt = 4 hrs?**

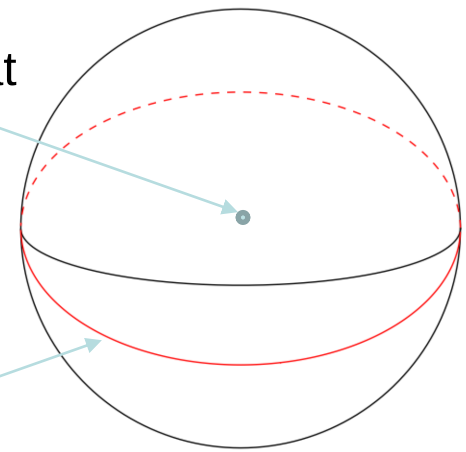


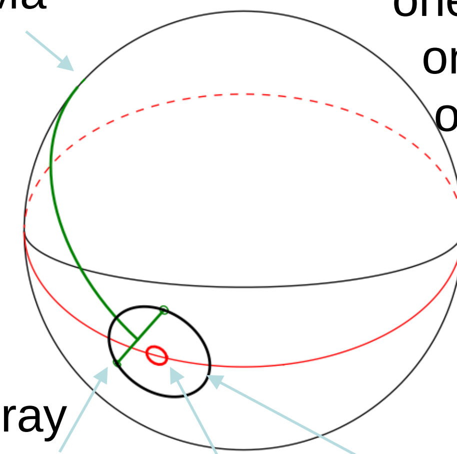
How do we pick "best" bright star during chop?

- **Minimize thermal effect**
  - Match cosine of angle between solar panel normal and sun direction
  - Allow any roll angle -13 to +13 deg on bright star
  - Not yet concerned with matching roll angle, seen in OS5
- **Consider "effective" V magnitude of bright star, after accounting for dead time for slew in both directions (to bright star and back to target star)**
- **Insist that effective V magnitude of bright star is brighter than 2.9, stellar angular diameter < 1 mas**
- **If cosine of solar angle is met exactly with more than 1 star, then select based on brightest effective V magnitude**

Graphical depiction of pointing (1)

- **Use observatory-centric coordinates, sky is ICRS (inertial)**

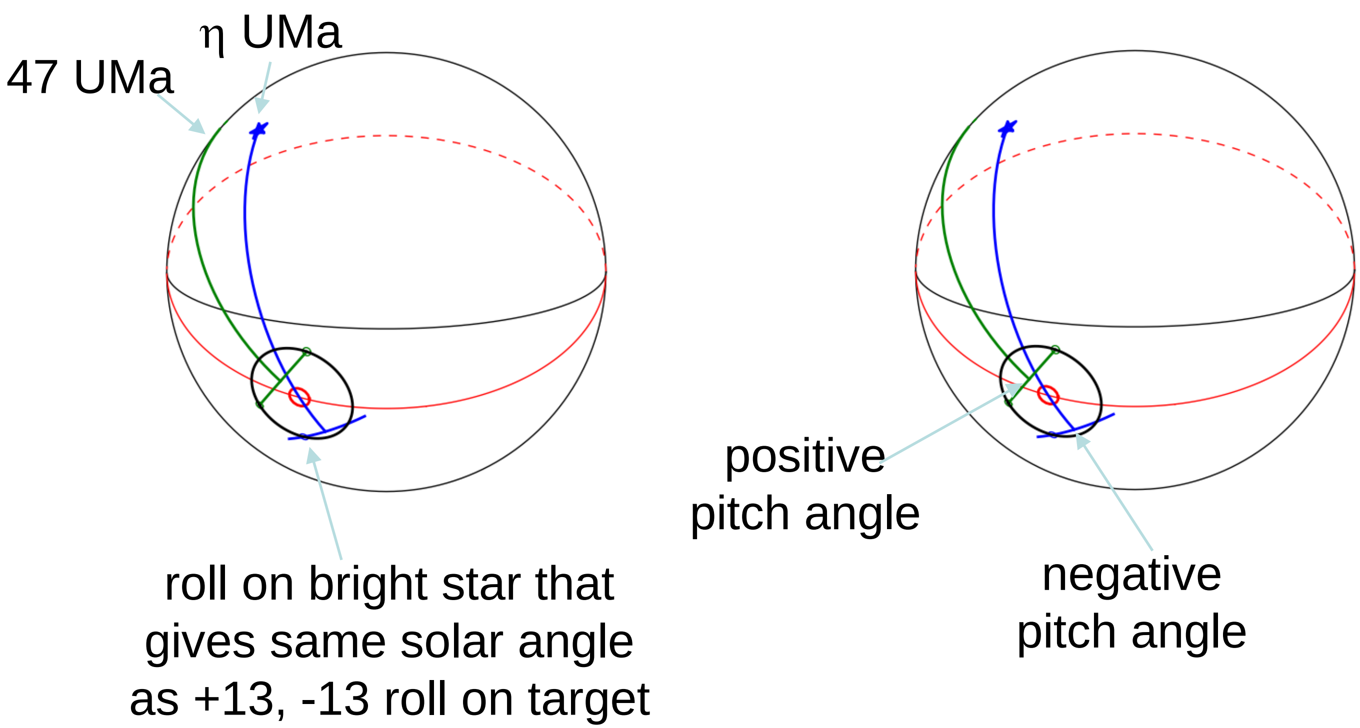




- **Solar panels will always face sun**
  - Pitch angles +/- 36 deg
  - Roll +/- 15 deg

Graphical depiction of pointing (2)

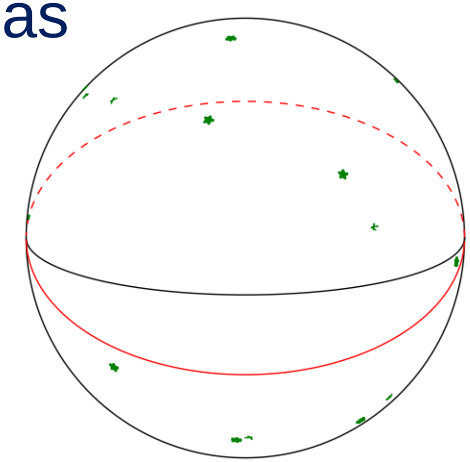
- **For each day, find "best" bright star**



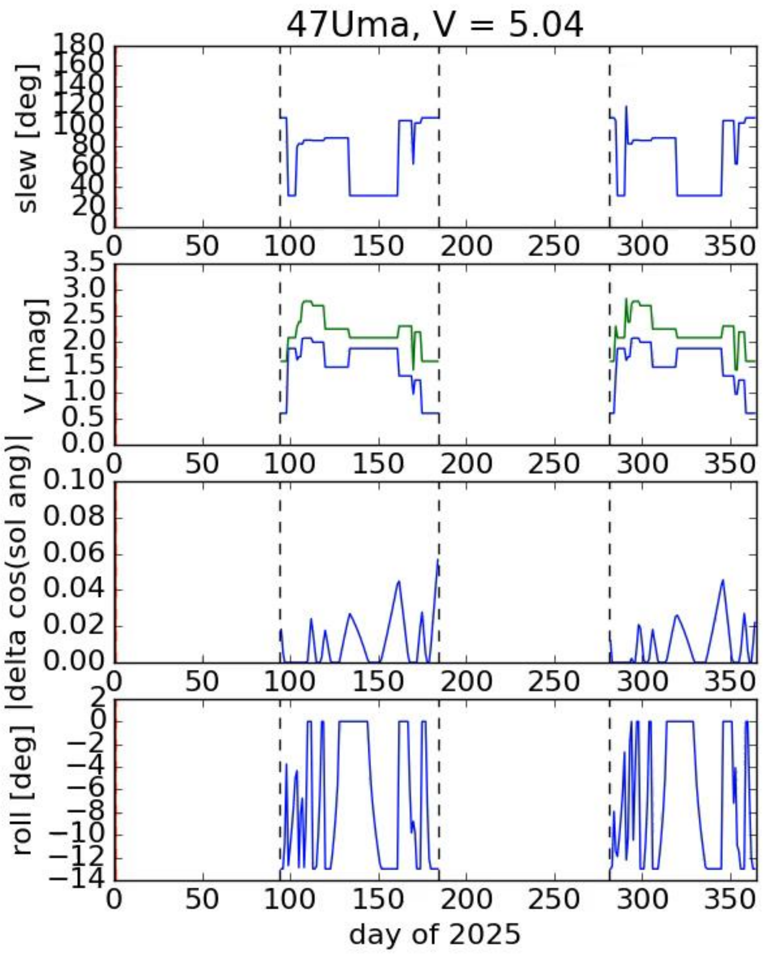
- **Best bright star will be different on different days of year**

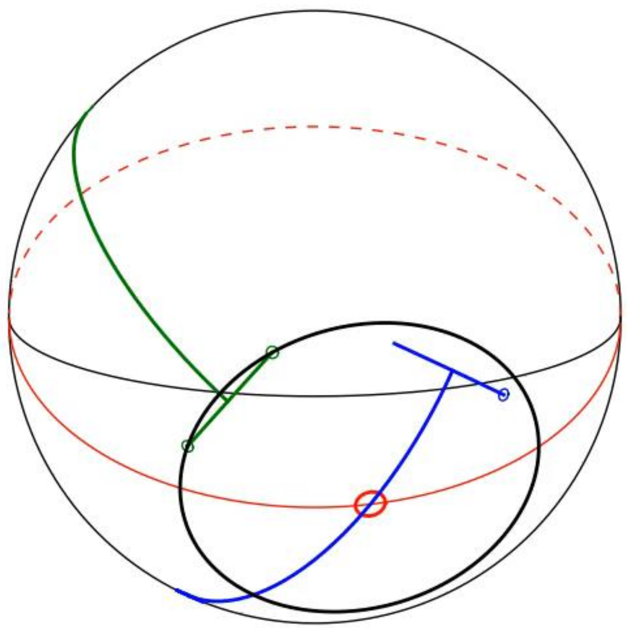
List of RV targets

- **Old list has ~ 15 stars with RV planets**
  - planets brighter than 10^{-10},
  - parent star $V < 9$
  - planet-star separation > 150 mas
- **~ 20 bright stars (without planets) get used**
  - stellar angular diameter < 1 mas
  - $V_{\mathrm{eff}} < 2.9$



Observing geometry of 47 UMa over 1 yr





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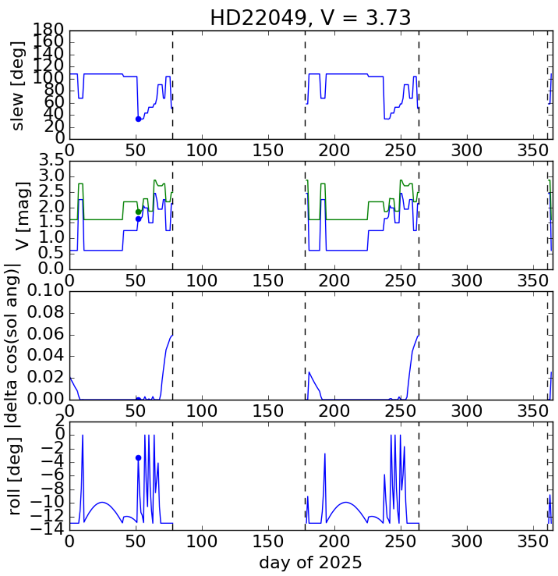
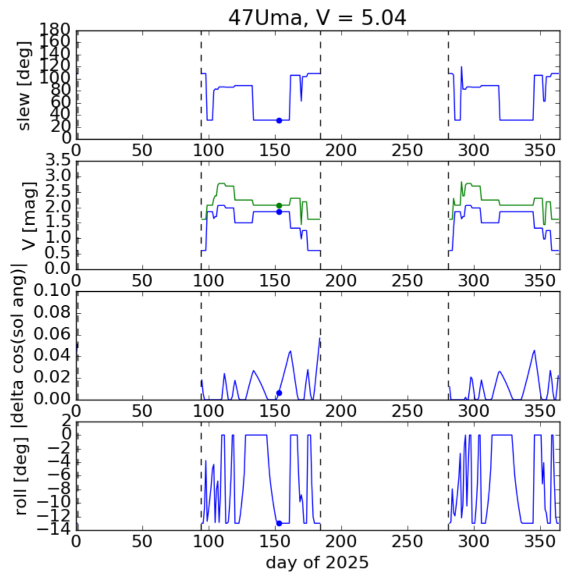
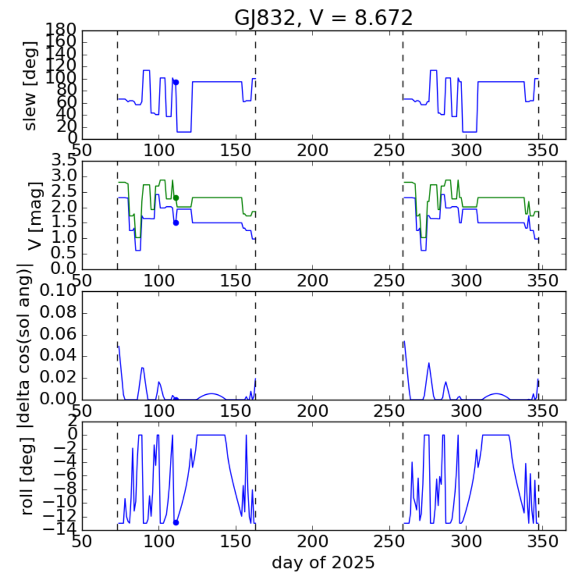
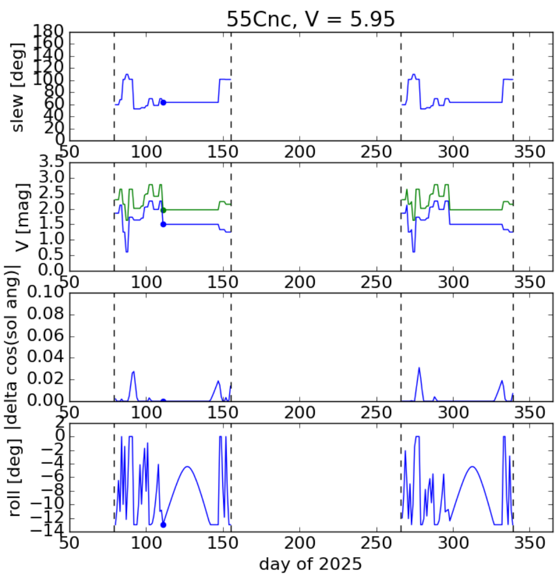
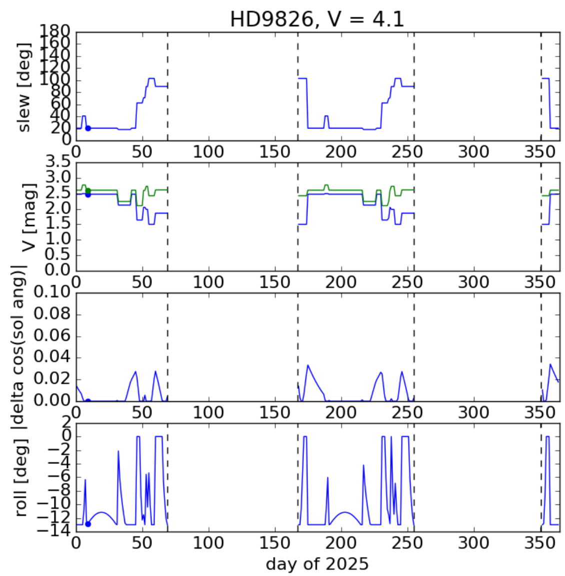
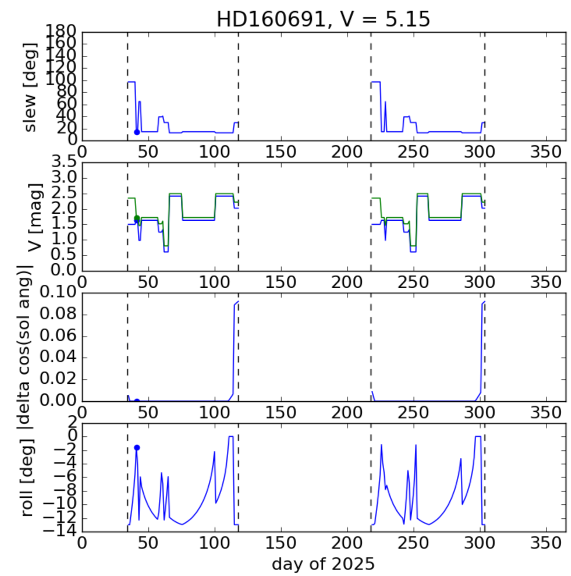




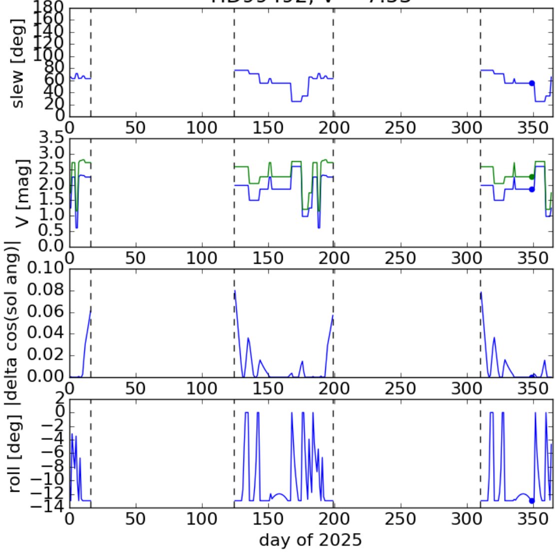




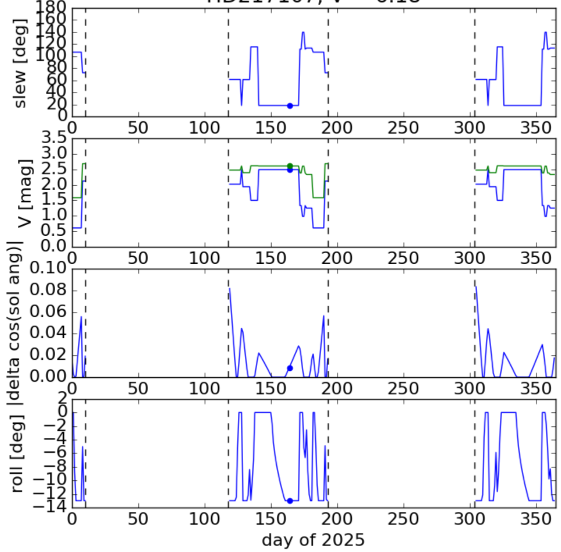




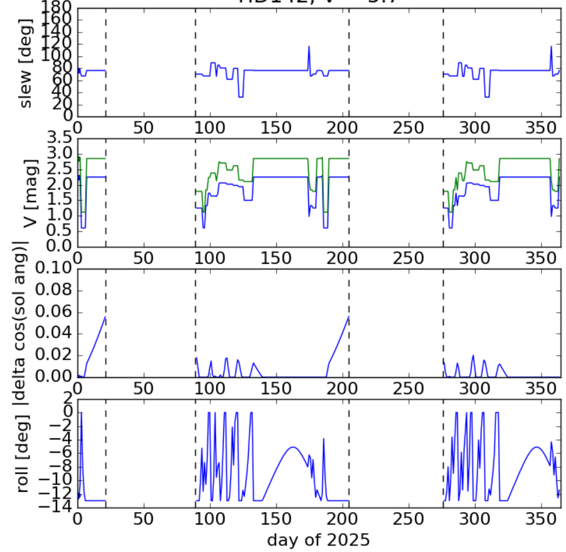
HD99492, V = 7.53



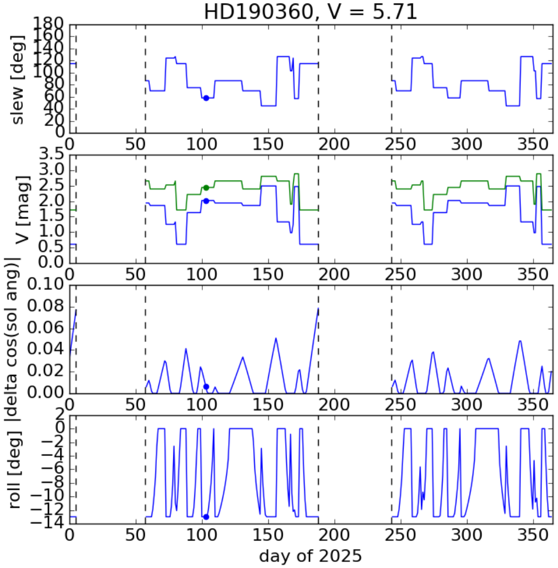
HD217107, V = 6.18



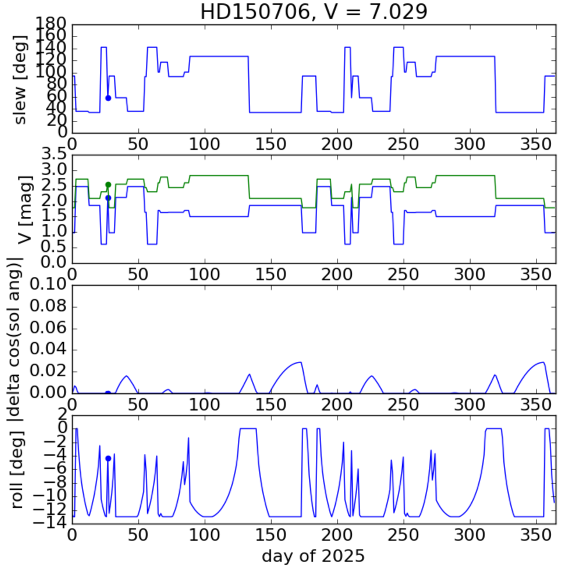
HD142, V = 5.7



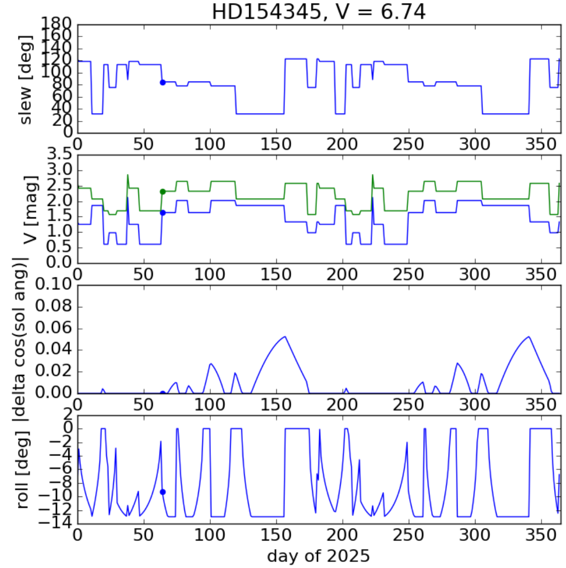
HD190360, V = 5.71

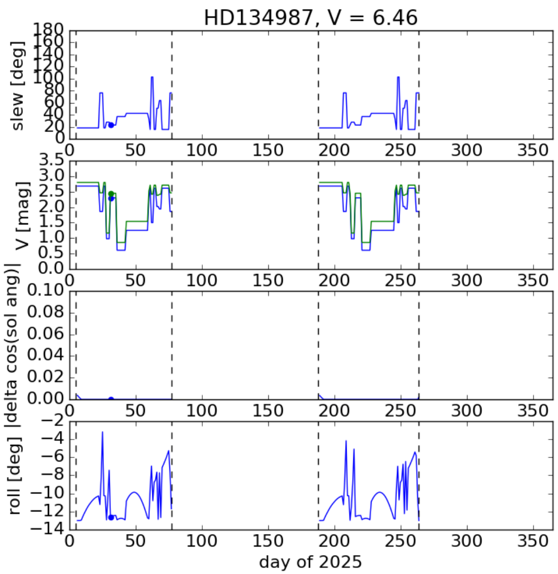


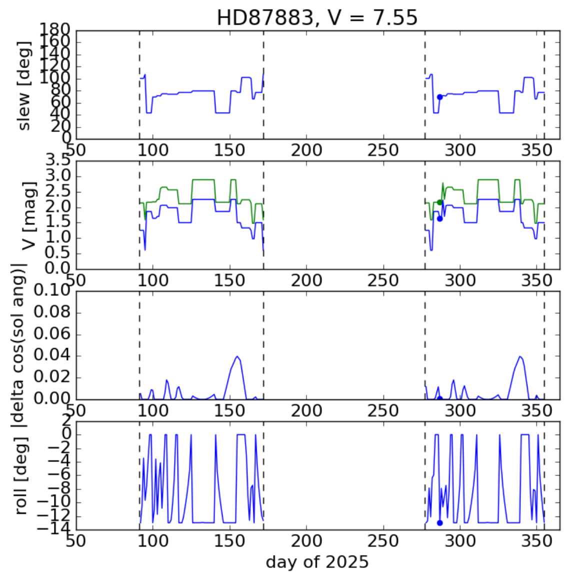
HD150706, V = 7.029

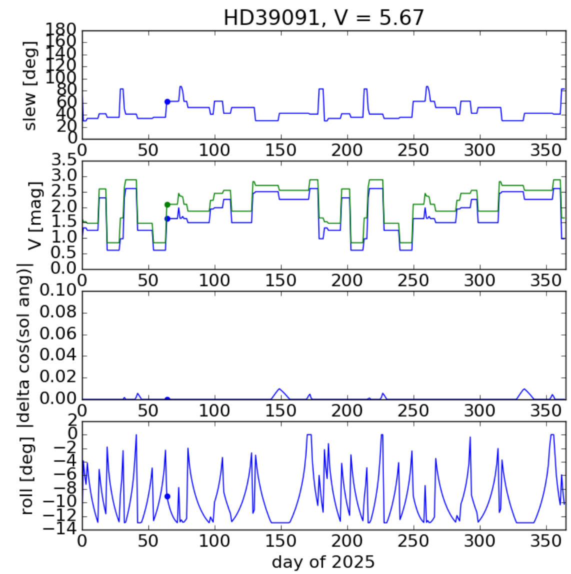


HD154345, V = 6.74



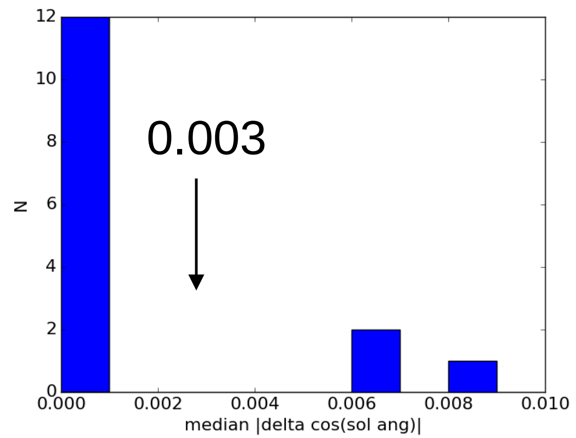

HD134987, V = 6.46
slew [deg]
V [mag]
|delta cos(sol ang)|
roll [deg]
day of 2025

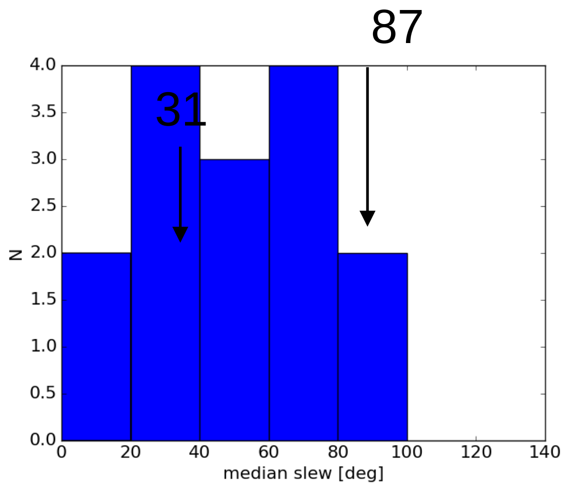

HD87883, V = 7.55
slew [deg]
V [mag]
|delta cos(sol ang)|
roll [deg]
day of 2025

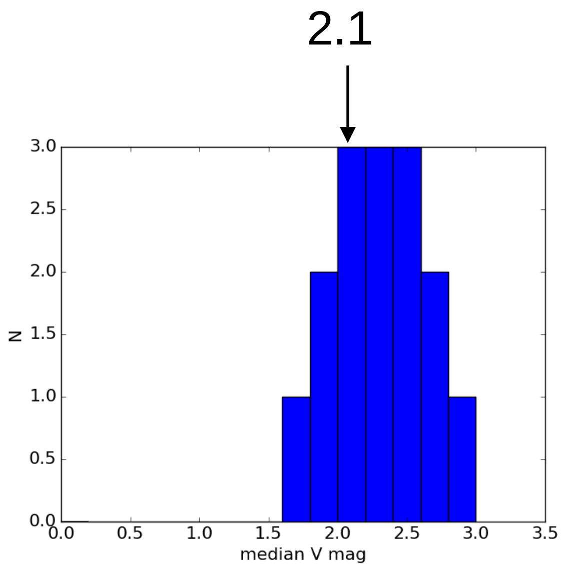

HD39091, V = 5.67
slew [deg]
V [mag]
|delta cos(sol ang)|
roll [deg]
day of 2025

How anomalous are 47 UMa's medians?

- **47 UMa has large median thermal effect, bright median star, and large median slew**
- **Case study was a match to median *V*, slew of case study does not match median**

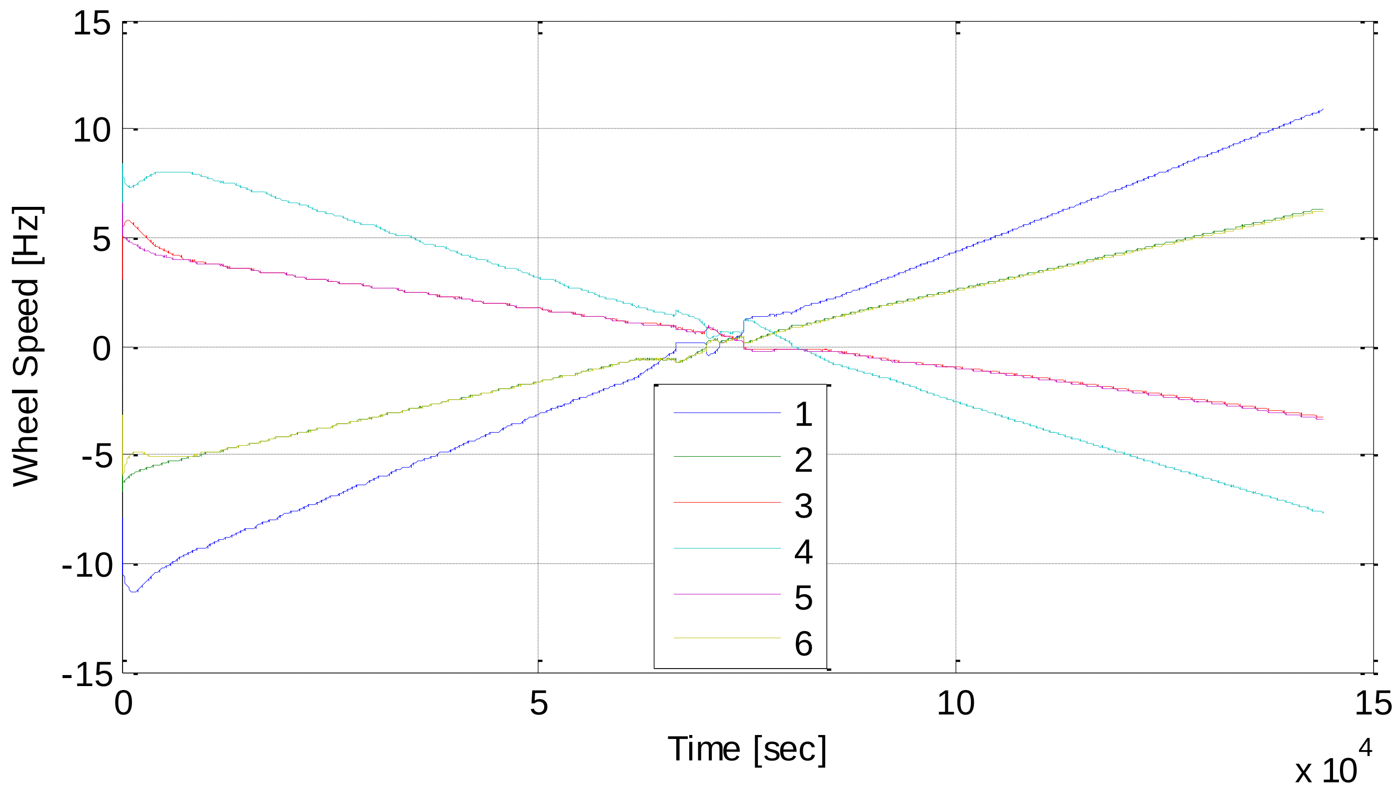






RWA changes affect differential measurements

- **Eric Stoneking Low Wheel Speed.pdf, evolution of 6 wheel speeds over ~ 1.5 days**



RWA changes (2/2)

- **This is RWA WFE jitter, with specific normalization**